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FINAL REPORT

"Plasma Physics of Planetary Magnetospheres"

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(NASA-CR-193780) PLASMA PHYSICS OF PLANETARY MAGNETOSPHERES Final Report (California Univ.) 13 p

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1. Barbosa, D.D. and W.S. Kurth, Theory and observations of electrostatic ion waves in the cold Io torus, J. Geophys. Res., 95, 6443-6450, 1990.

ABSTRACT

A study of the ELF plasma wave environment of the cold Io torus in Jupiter's magnetosphere is made. Voyager 1 data are presented which show three distinct types of electrostatic ion waves occurring there: the Buchsbaum ion-ion mode just below the proton cyclotron frequency f_{cp}, hydrogen Bernstein modes at $(n+\frac{1}{2})f_{cp}$, and lower hybrid waves near f_{LHR}. The presence of these waves at their characteristic frequencies is consistent with a predominantly heavy ion plasma composed of singly ionized sulfur and oxygen ions along with a small admixture of protons. The hydrogen Bernstein modes are tightly confined to the magnetic equator occurring within $\pm 4^\circ$ of it while the Buchsbaum mode is localized to the dense heavy ion plasma of the cold torus near the centrifugal equator. A general theory for excitation of the waves based on the ion pickup process is developed. Newly ionized S^+ and O^+ ions created out the extended neutral clouds of Io form a ring distribution in velocity space which is unstable to a large variety of plasma wave modes. The particular emissions found here are readily excited given the assumption that the heavy ions are unmagnetized. This condition allows for the propagation of strictly perpendicular wave modes free of electron Landau damping while sustaining large growth rates due to the pickup ions.

This paper is a follow-up of earlier work[1] on the nature of low-frequency plasma waves found by Voyager 1 in the cold Io torus of Jupiter. The gist of the work is to present evidence that both the Buchsbaum mode and hydrogen Bernstein modes are present in the cold torus. The theory of their excitation is based on a ring distribution of unmagnetized heavy ions that is formed through ion-neutral charge exchange processes with the extended neutral clouds of Io.[2-3] The theory gives a straightforward explanation of how low-frequency ion waves like the hydrogen Bernstein mode can be generated without undergoing strong electron Landau damping, a nettlesome problem that has plagued theorists for some time. Although it seemed at first that the paper would have an important but limited impact on the field, there was a serendipitous discovery of the waves also at Neptune with the same explanation offered (see paper #8), so that the paper's significance may be larger than previously thought.

2. Barbosa, D.D., W.S. Kurth, S.L. Moses, and F.L. Scarf, Z mode radiation in Jupiter's magnetosphere: the source of Jovian continuum radiation, J. Geophys. Res., 95, 8187-8196, 1990.

ABSTRACT

Voyager spacecraft observations of Z mode waves in Jupiter's magnetosphere are analyzed. The signal appears in wideband spectrograms as an intense narrowband emission separated from the broadband continuum radiation seen at higher frequencies by a deep emission gap. The assumption that the intensity minimum corresponds to the electron

plasma frequency organizes the data very well and provides a consistent interpretation of all spectral features in terms of plasma resonances and cutoffs. Several examples are given which demonstrate that the continuum radiation is composed of both left hand and right hand cutoff frequency, respectively. A survey of a representative sample of events reveals that the Z mode peak frequency lies close to the left hand cutoff frequency, suggesting that the observed characteristics of the emission are the result of wave reflection at the cutoff layer. In a substantial number of events, another distinct emission occurring near the upper hybrid resonance frequency is detected simultaneously with the Z mode. The entire set of observations gives strong support to the linear mode conversion theory of upper hybrid waves to continuum radiation mediated by the Z mode via the Budden radio window mechanism.

In 1979 Voyager spacecraft at Jupiter revealed the presence of the so-called Jovian continuum radiation trapped in the magnetospheric cavity of the planet.[4] Although one of the more interesting phenomena discovered by Voyager in the solar system, the identity of the source or its location has never been ascertained. Paper #2 is the first to present observational evidence of how and from where the emission is being generated. Z mode emissions had already been positively identified occurring on the edges of the magnetodisc plasma sheet,[5] however, the significance of this fact was not understood. Paper #2 has undertaken a careful analysis of all the VLF plasma wave emissions associated with the magnetodisc and found evidence for upper hybrid waves cospatial with the Z mode which gives a strong indication that a linear mode conversion mechanism whereby upper hybrid waves are converted into ordinary mode electromagnetic radiation mediated by the Z mode (so-called OJB theory[6-9]) is operative to produce the Jovian continuum radiation. The result gives a satisfactory account of the source of the continuum consistent with a previous assessment[10] and the scenario fits in very well with the plasma sheet boundary layer (PSBL) model of the magnetodisc published earlier.[11] The work is a definitive study of how continuum radiation is generated at Jupiter which will surely have an impact on the other planets as well. In fact, it has already influenced thinking on the source of myriametric radiation at Neptune (see #8, 9).

3. Barbosa, D.D. and W.S. Kurth, Beam-generated upper hybrid noise in Jupiter's outer magnetosphere, J. Geophys. Res., 95, 8177-8186, 1990.

ABSTRACT

Upper hybrid waves in Jupiter's outer magnetosphere are the subject of this paper which proposes a new theoretical model for their generation. Energetic electrons are assumed to be accelerated in the high-latitude auroral zone and stream away from the planet to the outer magnetosphere. The electrons travel along magnetic field lines located at the edges of the plasma sheet through a region which has the properties of a plasma sheet boundary layer similar to the terrestrial entity. The kinematic evolution of the electron beam results in a highly collimated field-aligned distribution which excites quasi-perpendicular upper hybrid waves through a so-called beam-anisotropic heat flux instability. The instability is dominated by anomalous cyclotron harmonic resonances in a parameter regime where the gyroradius of the beam electrons is comparable to the wavelength of the wave. Propagation of the upper hybrid waves across the magnetic field into a plasma density gradient produces a spectrum of Z mode waves which then undergo a linear mode conversion to ordinary mode electromagnetic radiation. The model successfully accounts for the observations of upper hybrid noise, Z mode emissions, and continuum radiation in the Jovian magnetosphere in a self-consistent coherent manner.

This paper is a theoretical follow-up work to the observation paper above (#2) on the Z mode and upper hybrid noise in the Jovian PSBL. The work describes a new model whereby energetic electrons accelerated in the auroral region stream out along field lines theading the PSBL and generate upper hybrid noise concurrently. The novel feature of the work is the "beam-anisotropic heat flux instability" invoked in generating the UH noise which doesn't require positive slope in the beam distribution for instability, only a beam thermal anisotropy where $a_{\parallel}/a_{\perp} >> 1$ for the beam. Such a mechanism helps explain why there should be occasions when UH noise is seen in a beam-plasma system with no corresponding emission at the electron plasma frequency (the canonical theory of which requires positive slope for the beam). The paper puts the final touches on the linear mode conversion mechanism applied to the generation of UH noise, Z mode noise, and continuum radiation in Jupiter's magnetosphere.

4. Barbosa, D.D., Radial diffusion of low-energy plasma ions in Saturn's magnetosphere, J. Geophys. Res., 95, 17167, 1990.

ABSTRACT

Analytic solutions to the steady-state radial diffusion equation allowing for a distributed source and sink of ions are presented. The diffusion space has absorption boundaries at the ends and is divided into two regions separated by an interior boundary where a discontinuity in diffusion and loss parameters is allowed to exist. The most general solution consists of a collection of point sources with adjustable weights to approximate an arbitrary continuous distribution of ion sources. The theory is applied to the study of thermal ion diffusion in Saturn's magnetosphere. It is concluded that a relatively large transport rate is required to conform with low-energy Voyager plasma measurements and a radial diffusion coefficient expressible as $D_{LL} = 4 \times 10^{-7} s^{-1} (L/6)^{3-4}$ is indicated. In such a fast diffusion regime cool O^+ ion densities at L = 2.8, 6, and 15 may be obtained from a single source in the form of the Dione-Tethys neutral H_2O cloud. Hot ion densities in the outer magnetosphere are obtained from ionization of Titan's neutral atomic clouds of hydrogen and nitrogen and ion pickup by the magnetospheric flow. The O^+ thermal ion model is compatible with a bi-modal distribution of neutral hydrogen in the magnetosphere with a Titan cloud $[H] \simeq 20\ cm^{-3}(L/20)$ in the outer magnetosphere and a low-density $[H] = 6\ cm^{-3} (6/L)^2$ hydrogen corona of either Saturnian origin or ring origin in the inner magnetosphere.

This paper gives the most sophisticated analytic treatment of radial diffusion with distributed sources and losses for planetary magnetospheres in the literature. The theory, embodied in the set of mathematical equations, is applied to the problem of the distribution of thermal plasma in Saturn's magnetosphere. The principal result of the analysis is to show that thermal O^+

ions with a source located in the Dione-Tethys plasma torus at $L \approx 6$ are transported throughout the magnetosphere as a consequence of a fast mode of radial diffusion operating at Saturn. Whereas previous studies[12-15] had assumed that radial diffusion was slow and ineffective in the inner magnetosphere, the present work has made a good case that the opposite is true with confirmation from other independent estimates of the diffusion rate based on high-energy charged particle loss rate.[16-19] The implications of this result are that plasma is not confined to the local neighborhood of where its source is but can spread out and interact with neutral gas clouds from other sources, i.e., Titan, the rings, and Saturn.

5. Barbosa, D.D., Bremsstrahlung X rays from Jovian auroral electrons, J. Geophys. Res., 95, 14969, 1990.

ABSTRACT

The spectrum of X rays from the planet Jupiter is calculated according to an auroral electron beam model. The electrons are assumed to be accelerated by a field-aligned potential drop and penetrate into the atmosphere as a Maxwellian beam of primaries which are scattered, degraded in energy, and merged with a population of ionization secondaries having a power law energy distribution. The soft X rays observed by the Einstein Observatory satellite are due to bremsstrahlung from the secondary electrons in the H_2 atmosphere. A good match to the X ray data is obtained if the power law spectral index of the secondary electrons $\gamma_e \approx 2$ yielding a power law slope for the photon flux $\gamma_X = \gamma_e + 1 \approx 3$. The X ray intensity is best reconciled with a beam of primaries having a characteristic energy 30-100 keV and penetrating the homopause with an auroral energy flux typically of 10-20 ergs $cm^{-2}s^{-1}$ but no greater than 50 ergs $cm^{-2}s^{-1}$.

This paper presents a new theory of X ray emission from the Jovian aurora. Over the past decade most researchers in the field have been inclined to believe that the aurora is generated by precipitating energetic heavy ions, viz. S^+ and O^+. When soft X rays were detected from Jupiter,[20] the simplest interpretation of them was in terms of electron bremsstrahlung, but there were theoretical obstacles to this interpretation that led to the alternate competing hypothesis of K-shell line emission from S^+ and O^+. Paper #5 develops a quantitative theory of how the observed X rays can be generated by auroral secondary electrons which have been formed from a higher-energy primary beam of precipitating electrons. The theory gives a simple description of the X ray spectral properties that result from the auroral electron bremsstrahlung in an H_2 atmosphere of the giant planets. The key feature of the model is the allowance for primary electrons to penetrate deep into the atmosphere where secondary electrons can scatter off of a dense atmosphere at a sufficiently rapid rate to account for the observed soft X ray intensity.

6. Barbosa, D.D., Bremsstrahlung X ray spectra of Jupiter and Saturn: predictions for future planetary spacecraft, Geophys. Res. Lett., 17, 1029, 1990.

ABSTRACT

Calculations of X ray spectra due to bremsstrahlung from precipitating auroral electrons at Jupiter and Saturn are presented. The model assumes that a field-aligned potential drop accelerates a primary beam of electrons into the atmosphere where a population of secondary electrons having a power law energy dependence is generated. The spectrum at Jupiter is normalized ot the soft X ray observations of Metzger et al. (1983) at the low-energy end and constrained at the high-energy end by UV auroral energy requirements. The spectrum at Saturn is constructed by analogy to the Jovian case allowing for variation of the beam energy, energy flux, and scale size of the Saturnian aurora. The results indicate that a significant flux of X rays is emanating from both planets which may serve as a basis for conducting planetary X ray astronomy as a part of future spacecraft missions to the planets.

This paper published in Geophysical Research Letters announces the results of paper #5 with the idea of asking whether the X ray fluxes of Jupiter and Saturn (appropriately scaled for the different dynamics and energetics of the two giant planets) are large enough that an observational program by an orbiting or flyby spacecraft like ULYSSES or CASSINI is worthwhile. The answer is an emphatic yes: a very valuable data set would be obtained that would give direct measurements of auroral electron activity via bremsstrahlung X rays to complement ultraviolet wavelength observations.

7. Gurnett, D.A., W.S. Kurth, R.L. Poynter, L.J. Granroth, I.H. Cairns, W.M. Macek, S.L. Moses, F.V. Coroniti, C.F. Kennel, and D.D. Barbosa, First plasma wave observations at Neptune, Science, 246, 1494, 1989.

ABSTRACT

The Voyager 2 plasma wave instrument detected many familiar plasma waves during the encounter with Neptune, including electron plasma oscillations in the solar wind upstream of the bow shock, electrostatic turbulence at the bow shock, and chorus, hiss, electron cyclotron waves, and upper hybrid resonance waves in the inner magnetosphere. Low-frequency radio emissions, believed to be generated by mode conversion from the upper hybrid resonance emissions, were also observed propagating outward in a disklike beam along the magnetic equatorial plane. At the two ring plane crossings many small micrometer-sized dust particles were detected striking the spacecraft. The maximum impact rates were about 280 impacts per second at the inbound ring plane crossing, and about 110 impacts per second at the outbound ring plane crossing. Most of the particles are concentrated in a dense disk, about 1000

kilometers thick, centered on the equatorial plane. However, a broader, more tenuous distribution also extends many tens of thousands of kilometers from the equatorial plane, including over the northern polar region.

Exciting new plasma wave observations made by Voyager 2 at Neptune are described in this paper. Prior to the encounter no one knew what to expect except for the usual assortment of standard plasma wave emissions (e.g., ECH waves). That is, it was not known whether Neptune even had a magnetic field or whether interesting auroral zone effects might be observed as the spacecraft made a very close pass of the planet at high latitudes. Well it turns out that Neptune has a very interesting magnetosphere full of surprises and oddities. Equatorial ECH waves were of course detected and their location precisely defined by the plasma instrument has led to a refinement of the magnetic field model (OTD2). One of the most important findings of the plasma wave experiment is the detection of periodic VLF radio bursts that are seen when the spacecraft is at the magnetic equator. The radio emission have been associated with intense upper hybrid resonance emissions occurring in the inner magnetosphere which are thought to be the source of the radio waves. The data represent one of the best experimental verifications of the Oya-Jones-Budden OJB radio window mode conversion mechanism (see paper #8 and 9) ever obtained in space physics.

8. Barbosa, D.D., W.S. Kurth, I.H. Cairns, D.A. Gurnett, and R.L. Poynter, Electrostatic electron and ion cyclotron harmonic waves in Neptune's magnetosphere, Geophys. Res. Lett., 17, 1657, 1990.

ABSTRACT

Voyager 2 observations of electrostatic electron and ion cyclotron waves detected in Neptune's magnetosphere are presented. Both types of emission appear in a frequency band above the electron and ion (proton) cyclotron frequencies, respectively, and are tightly confined to the magnetic equator occurring within a few degrees of it. The electron cyclotron waves are interpreted as electron Bernstein modes including an intense upper hybrid resonance emission excited by an unstable loss cone distribution of low-density superthermal electrons. The ion cyclotron waves are interpreted as hydrogen Bernstein modes including an intense lower hybrid resonance emission excited by an unstable ring distribution of low-density pickup N^+ ions deriving from the satellite Triton.

This paper presents Voyager 2 observations of ECH and ICH waves detected in Neptune's magnetosphere. As with all other ECH wave events found in planetary magnetospheres, the Neptune ECH waves occur in close proximity to the magnetic equator. By way of comparison, the results show outstanding agreement with the magnetic equator predicted by the OTD2 model which is the most current magnetic field model obtained by the magnetometer team. Just after closest approach an ICH event was found occurring very close to the magnetic equator as well. Based on the similarities of this emission to that found at Jupiter in the cold Io torus (see paper #1), the Neptune ICH waves were interpreted as electrostatic hydrogen Bernstein modes generated by an unstable pickup ion distribution of heavy ions (N^+ from Triton). Thus, we see that the earlier

Jupiter work on low-frequency equatorial ion waves has paid a big dividend in aiding the interpretation of the Voyager 2 Neptune wave observations.

9. Kurth, W.S., D.D. Barbosa, D.A. Gurnett, R.L. Poynter, and I.H. Cairns, Low-frequency radio emissions at Neptune, Geophys. Res. Lett., 17, 1649, 1990.

ABSTRACT

The Voyager 2 plasma wave receiver detected weak radio emissions from Neptune's magnetosphere in the frequency range of 3-60 kHz. The emissions occurred in bursts lasting for typically 1.5 hours, often occurring twice per planetary rotation. Most of these radio bursts were detected within several degrees of the magnetic equatorial plane. During the passage through the magnetosphere, electrostatic upper hybrid resonance bands were observed close to the magnetic equator in conjunction with intensifications of the radio emissions at frequencies close to and above the upper hybrid bands. Further, near closest approach, the radio emissions were observed to cross the right-hand cutoff frequency with no apparent attenuation. We conclude that the Neptunian radio emissions below about 60 kHz are produced by mode conversion from the upper hybrid waves and propagate in the ordinary mode into beams within about 12° of the magnetic equator. There is also evidence of an extraordinary mode emission at about 60 kHz which is apparently generated by an entirely different source from the escaping continuum radiation.

This paper expands on the details of low-frequency radio emissions detected by the plasma wave instrument on Voyager 2 at Neptune. The most prominent feature of the radio waves is their periodic occurrence twice per planetary rotation, the pulsed signal being received when the spacecraft is at the magnetic equator defined by the OTD2 model. The paper goes further in showing that the source of the radio waves is located at the magnetic equator and is intimately related to the occurrence of intense upper hybrid emissions which are also localized to the equator. The interpretation is that the upper hybrid waves mode convert to electromagnetic ordinary mode waves which escape from the magnetosphere in a radiation beam that is oriented along the magnetic equator with a beam width of $\pm 12^\circ$ about it. The data also show quite convincingly the relation of the radio wave spectrum to the appearance of upper hybrid waves when the spacecraft passes through the equator at 10 R_N. These results may provide some of the best evidence available in support of the Oya-Jones-Budden linear mode conversion theory for the generation of radio waves. In this regard the Neptune encounter has truly been a scientific success as a solar system laboratory for testing viable theories of plasma-physical processes.

10. Barbosa, D.D., Ion pickup, scattering, and stochastic acceleration in the cometary environment of P/Giacobini-Zinner, AGU Monograph on Cometary Plasma Processes, edited by A.D. Johnstone, p.291, 1991.

ABSTRACT

This paper gives a brief review of observations and theory related to the scattering and acceleration of cometary pickup ions with emphasis on comet P/Giacobini-Zinner. A comparison of the regions upstream and downstream of the bow shock is made to assess the relative merits of each as a site for stochastic acceleration of ions above the pickup energy through interaction with low-frequency magnetohydrodynamic waves. In the upstream region the data are most consistent with a model where pickup ions generate a low level of MHD waves but remain relatively scatter-free following trajectories of transverse to the interplanetary magnetic field at an oblique angle to the solar wind velocity. In the downstream region the intense level of magnetic fluctuaions gives rise to a rapid isotropization of the ions and a second-order stochastic (Fermi) acceleration. The properties of the MHD power spectrum are related to the energetic ion spectrum in the framework of a leaky box model where the bulk of the acceleration occurs downstream of the shock throughout the cometosheath. Very good agreement of the observations with theory is evident for both P/Giacobini-Zinner and P/Halley.

This is a topical review concerning models of ion acceleration around comets with emphasis on P/Giacobini-Zinner. The paper spells out unambiguously why the primary acceleration region for the stochastic acceleration of cometary pickup ions is downstream of the bow shock rather than upstream as most comet theorists assumed prior to the publication of Ref. 21. The cometary environment provides one of the best verifiable examples of how a turbulent spectrum of MHD waves can produce a population of energetic ions through stochastic wave-particle interactions,[22-23] and these observations will be cited extensively in future work dealing with the acceleration of ions in planetary magnetospheres where a high level of MHD waves is present

SUMMARY OF RESEARCH REPORTS NAGW-1558

Papers previously cited for NRA 88 as in press:

Barbosa, D.D., Minimal Joule dissipation models of magnetospheric convection, Pure Appl. Geophys. 127, 473-489, 1988.

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Barbosa, D.D., Stochastic acceleration of cometary pickup ions: the classic leaky box model, Astrophys. J., 341, 493-496, 1989.

New papers acknowledging NAGW-1558 and other NASA support:

1. Barbosa, D.D. and W.S. Kurth, Theory and observations of electrostatic ion waves in the cold Io torus, J. Geophys. Res., 95, 6443-6450, 1990.

2. Barbosa, D.D., W.S. Kurth, S.L. Moses, and F.L. Scarf, Z mode radiation in Jupiter's magnetosphere: the source of Jovian continuum radiation, J. Geophys. Res., 95, 8187-8196, 1990.

3. Barbosa, D.D. and W.S. Kurth, Beam-generated upper hybrid noise in Jupiter's outer magnetosphere, J. Geophys. Res., 95, 8177-8186, 1990.

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Barbosa, D.D. and W.S. Kurth, Theory and observations of electrostatic ion waves in the cold Io torus, EOS Transactions AGU, 70, 451, 1989.

Barbosa, D.D., Scattering and stochastic acceleration of pickup ions by MHD turbulence in the post-shock region of P/Giacobini-Zinner, AGU Chapman Conference on Cometary Plasma Processes, Guildford, England, July 17-21, 1989.

Barbosa, D.D., Global magnetospheric convection as determined from minimal Joule dissipation theory, Sixth Scientific Assembly IAGA, Exeter, England, July 24 - August 4, 1989.

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